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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(89)90573-X

AN EXPLICIT PARTITION OF THE FUSION-LIKE CROSS SECTION

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Received 23 March 1989

The evaporation residue cross section for fusion-like reactions of 309 MeV $^{14}N+{}^{159}Tb$ has been decomposed into cross sections for complete fusion and a number of specific incomplete fusion channels using a novel technique involving light-particle–KX-ray coincidences With this partition it is possible to successfully describe the incomplete momentum transfer observed in velocity spectra of evaporation residues from a very similar system

A well known feature of heavy ion reactions at intermediate energies is the abundance of fast light particles at small angles [1,2] For the same class of systems, fission folding angle measurements [3] and measurements of evaporation residue (ER) velocity distributions [4] show that there is an incomplete transfer of the projectile's momentum to the compound nucleus in fusion-like reactions Although the emission of fast light particles in the beam direction is generally believed to be the sole cause of this incomplete momentum transfer, a *quantitative* account based on an explicit decomposition of the fusion-like cross section has not yet been presented at energies where complete fusion no longer dominates Because of the many competing processes leading to fast light particle emission at small angles, such a quantitative description is by no means trivial

We report here recent results obtained by combining the KX-ray method [5] with a plastic wall for the detection of fast light particles in the forward hemisphere By making use of a novel method suggested by Balster [6], ER cross sections for complete fusion and a number of incomplete fusion channels have been obtained The sum of these cross sections comprises the yield for fusion–evaporation reactions, and with neutron cross sections deduced under the assumption of charge symmetry the resulting evaporation residue velocity distributions and the average momentum transfer have been calculated under simplifying assumptions

A beam of 309 MeV $^{14}N^{6+}$ ions from the KVI cyclotron was used to bombard a ^{159}Tb target of areal density 5 mg/cm^2 Fast light particles (FLPs) were detected in an array of 31 phoswich detectors [7] (the "plastic wall"), each with an area of 6 5×6 5 cm^2, which covered a solid angle of approximately 1 5 sr in the forward hemisphere A high resolution Ge detector positioned at 90° to the beam axis was used to detect the characteristic KX-rays from the evaporation residues Four silicon detector telescopes, positioned at angles from 150° to 173°, were used for the detection of H and He particles In addition, a phoswich detector with a thin (200 μm) ΔE scintillator and an area of 6 5×6 5 cm^2, was positioned at 140° to the beam axis and used to detect light charged particles in coincidence with the KX-rays Events were triggered either by one of the silicon telescopes or by a coincidence between one of the backward detectors (silicon or backward phoswich) and the X-ray detector The phoswich detectors in the plastic wall were read as slaves

The cross section for production of an evaporation residue of atomic number Z_{ER} can be obtained by measuring the coincident cross section, $\sigma_{H/He}(Z_{ER})$, and multiplicity, $M_{H/He}(Z_{ER})$, for evaporation of H or He, e g

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$$\sigma(Z_{ER}) = \frac{\sigma_H(Z_{ER})}{M_H(Z_{ER})} = \frac{\sigma_{He}(Z_{ER})}{M_{He}(Z_{ER})} \quad (1)$$

In the analysis presented here, events have been sorted into complete fusion and various incomplete fusion channels according to the number and type of FLPs detected in the plastic wall, and eq (1) has been used to extract separately for each channel the residue Z distributions The sum of the individual residue cross sections gives the total cross section for each channel The yield of residues corresponding to no charged particle evaporation was estimated by extrapolating the measured Z_{ER} distribution The contribution of this residue ranged from <2% for the CF channel to 16% for the 2He channel A simple energy cut approximately 5 MeV/u above the Coulomb energy constituted an operational definition of "fast" light particles The requirement of a backward-evaporated particle as an event trigger automatically selected fusion-like events This allowed us to reject quasielastic reactions followed by sequential decay of the projectile-like fragment, which are a strong source of FLPs at small angles [2]

Extending the method of Balster [6], evaporation multiplicities, $M_H(Z_{ER})$ and $M_{He}(Z_{ER})$, were obtained from measurements of the nuclear charges of evaporation residues (Z_{ER}) and fast light particles (Z_{FLP}) in coincidence with an evaporated H or He, by utilizing the relations

$$Z_P + Z_T - Z_{ER} - Z_{FLP} \equiv Z_{evap}$$
$$= M_H(Z_{ER}) + 2M_{He}(Z_{ER}) , \quad (2)$$

$$\frac{M_H(Z_{ER})}{M_{He}(Z_{ER})} = \frac{\sigma_H(Z_{ER})}{\sigma_{He}(Z_{ER})} \quad (3)$$

Here Z_P and Z_T are the atomic numbers of the projectile and target, Z_{evap} is the total nuclear charge of all evaporated H and He, and $M_{H/He}(Z_{ER})$ and $\sigma_{H/He}(Z_{ER})$ are the average multiplicities and cross sections for H and He evaporation coincident with the production of evaporation residues of charge Z_{ER} Eqs (2) and (3) can be combined with eq (1) to give the following expression for the residue production cross sections

$$\sigma(Z_{ER}) = \frac{\sigma_H(Z_{ER}) + 2\sigma_{He}(Z_{ER})}{Z_{evap}} \quad (4)$$

Differential cross sections, $d\sigma_H(Z_{ER})/d\Omega$ and $d\sigma_{He}(Z_{ER})/\Omega$, were extracted by fitting KX-ray energy spectra generated in coincidence with an evaporated H or He particle detected in the backward phoswich detector for each of the fusion-like channels This fitting procedure is described in some detail in ref [5] Angular distributions of evaporated H and He were measured at extreme backward angles with the silicon detector telescopes, and these measurements were used to deduce the anisotropy of the center-of-mass evaporation angular distributions for each fusion-like channel This anisotropy was in turn used to obtain the angle-integrated cross sections, $\sigma_H(Z_{ER})$ and $\sigma_{He}(Z_{ER})$

We wish to emphasize that the identification of the evaporation residues via their KX-rays offers an important advantage over more intrusive detection techniques, in that it provides an automatic angular and energy integration of the ER yields The angular distributions of FLPs detected in coincidence with the ERs are therefore not biased by the experimental geometry

Absolute cross sections were obtained by normalizing to the charge deposited in the Faraday cup The overall efficiency of the X-ray detector, determined using calibrated X-ray and gamma sources, was 0 12%±0 01% The multiplicities for KX-ray emission were taken to be 0 6 for even-Z residues and 1 2 for odd-Z residues, the values used by Balster et al [5] for $^{14}N+^{159}Tb$ at energies from 8 to 17 MeV/u These values are also in reasonable agreement with those reported by Pinston et al [8] for reactions of $^{14}N+^{169}Tm$ and $^{14}N+^{174}Yt$ at 30 MeV/u

The measured ER cross sections for complete fusion and the strongest incomplete fusion channels are presented in fig 1 and table 1, along with the same cross sections corrected for the incomplete angular coverage of the plastic wall The correction to the CF cross section also included subtraction of a cross section for the ICF channel with one fast neutron out, which was assumed to be the same as that for the 1p channel The complete fusion cross section is 196±47 mb, and the total cross section for fusion-like processes is 815±165 mb

The fraction of the ER cross section corresponding to complete fusion, 0 24±0 08, is in reasonable agreement with systematics [9] The validity of such a comparison is questionable, however, since fission

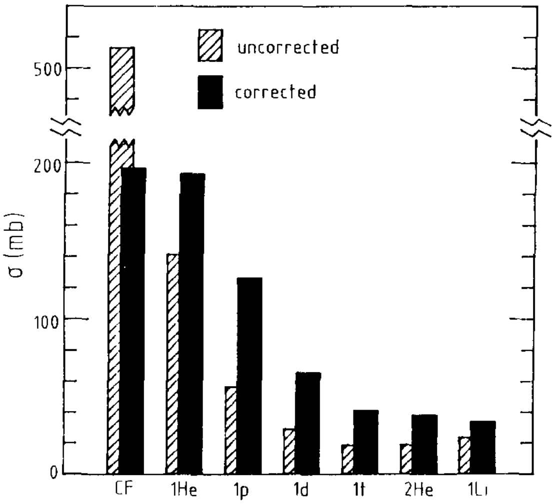

Fig 1 Cross sections for various fusion-like channels of 309 MeV $^{14}N+^{159}Tb$ The solid bars are cross sections corrected for the incomplete coverage of the plastic wall

Table 1
Cross sections (in mb) for the strongest fusion-like channels The cross sections in the last column include corrections for the incomplete angular coverage of the plastic wall The quoted uncertainties reflect relative errors only In the case of the uncorrected cross sections they are the statistical uncertainties there is an additional uncertainty of ±20% due to systematic effects

Channel	σ_{fus}	
	uncorrected	corrected
CF	513±12	196±25
1p	56± 4	126±16
1n [a]	–	126±16
1d	29± 2	65± 9
1t	18± 2	41± 6
1He	141± 8	192±17
1Li	24± 3	34± 5
2He	19± 3	38± 7

[a] Assumed equal to the 1p cross section

completes more strongly with evaporation in $^{14}N+^{159}Tb$ than in the much lighter systems of ref [9] On the basis of semi-inclusive H evaporation cross sections (i e , not coincident with a residue KX-ray), which include contributions from fusion–fission events, and under the assumption that the H evaporation multiplicity is independent of whether fission occurs, we estimate a cross section of 300±120 mb for fusion-like events leading to fission, of which 260±120 mb belongs to the complete fusion channel Inclusion of these estimates changes the ratio of complete fusion to all fusion-like events to 0 41±0 14, which is well above the systematics reported in ref [9] This may be due in part to an underestimate of pre-equilibrium neutron emission

The experiment reported here provides more detailed information about the partition of the fusion-like cross section than the measurements of evaporation residue velocities or fission folding angles commonly used to study incomplete fusion While ER velocity distributions have been unfolded into CF and ICF components, for example [9,10], a separation of the ICF component into specific channels is not feasible at the energy of the present work, where many ICF channels contribute to the ER yields The result reported here therefore provides a unique opportunity for testing quantitatively the common assumption that the momentum deficit observed in fusion-like reactions at these energies is due solely to the emission of FLPs in the forward direction Toward that end, we have performed calculations of the ER velocity distributions corresponding to our measured fusion-like cross sections The calculation assumes exponential center-of-mass angular distributions for the FLPs, with slopes extracted from our measurements The center-of-mass velocity distributions of the FLPs are assumed to be gaussians centered at the center-of-mass velocity of the projectile The calculation further assumes that the final ER velocities are described by a maxwellian distribution in the rest frame of the primary, reduced compound nucleus (RCN) and that their angular distributions are isotropic in that frame Fig 2 shows in some detail the results of the calculation for $\theta=16°$ Velocity distributions for each channel are shown, along with the composite distribution The linear momentum transfer, ρ, extracted in the usually way [11] from the composite distribution is 0 88, which is consistent with the systematics given in ref [12]

A more detailed comparison with momentum transfer measurements is presented in fig 3, where calculations of the type described above are compared with ER velocity distributions reported recently [13] for the very similar system $^{14}N+^{154}Sm$ at 19 MeV/u It should be noted that the calculation gives absolute values for the differential cross sec-

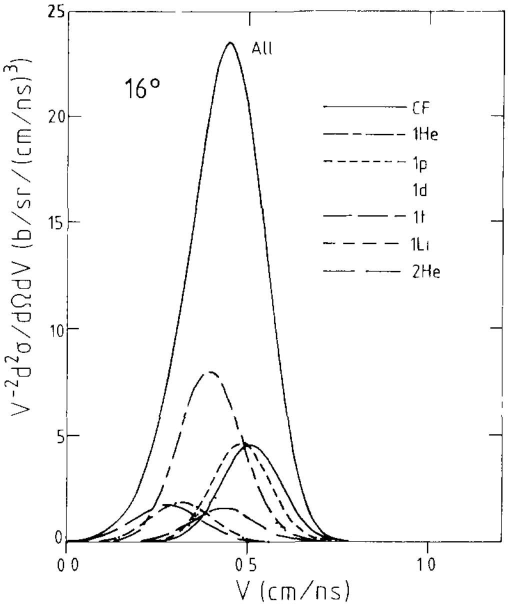

Fig 2 Evaporation residue velocity distributions for 309 MeV $^{14}N+^{159}Tb$, calculated as described in the text from the measured cross sections of fusion-like channels The curve labeled "All" includes a contribution from the 1n channel, which was assumed to be identical to the 1p component

tion, $V^{-2}\,d^2\sigma/d\Omega\,dV$, based solely on our measured $^{14}N+^{159}Tb$ cross sections Only the kinematical aspects of the calculation make use of the projectile, target, and bombarding energy, and the resulting differential cross sections are not normalized in any way to the $^{14}N+^{154}Sm$ data The impressive agreement between the calculated curves and the data points suggests that the interpretation of these measured velocity distributions as resulting from incomplete fusion reactions is quantitatively consistent with our explicit partition of the fusion-like cross section

In summary, we have decomposed the ER cross section of $^{14}N+^{159}Tb$ at 22 MeV/u into complete fusion and a number of specific incomplete fusion channels A novel technique involving indirect detection of the ERs was employed, with the advantage that the biasing effects inherent in direct detection of the ERs were avoided With our measured partition of the fusion-like cross section it is possible to calculate, under simple assumptions about the effects of subsequent light particle evaporation, the velocity distributions of the resulting evaporation residues The emission of fast α particles is seen to be an essential element in the quantitative decomposition of these velocity distributions In addition to providing a quantitative explanation of incomplete momentum transfer in fusion-like reactions, the partition into specific channels provides important input for inves-

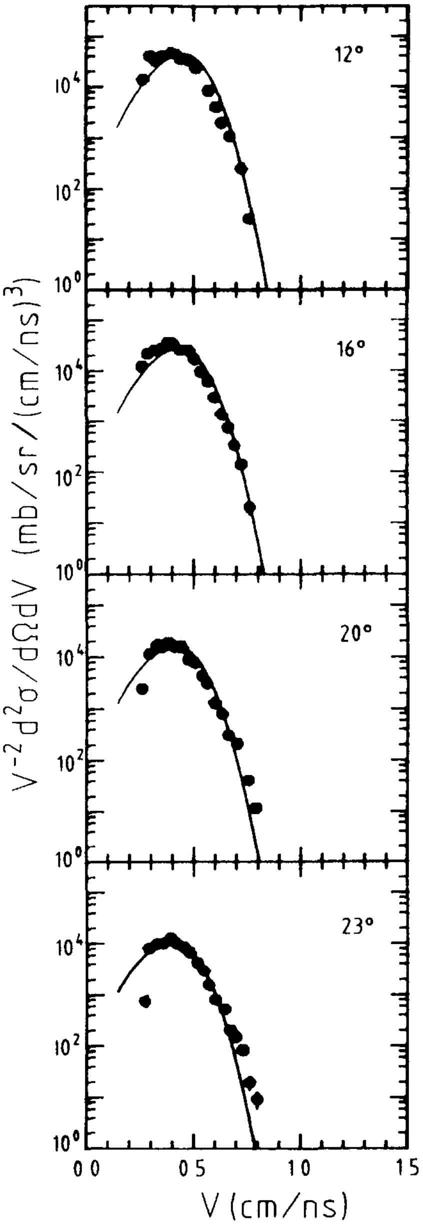

Fig 3 Comparison of residue velocity distributions calculated using the measured $^{14}N+^{159}Tb$ fusion-like cross sections with the distributions reported in ref [13] for 261 MeV $^{14}N+^{154}Sm$

tigating the dynamics of the incomplete fusion process

This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), with financial support from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)

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